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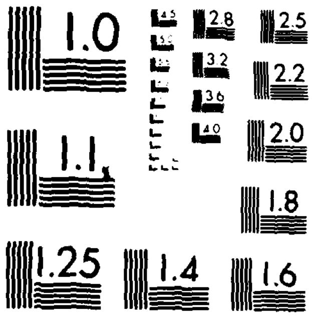

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MEMORANDUM REPORT ARBRL-MR-03299

COMPARISON OF TDNOVA RESULTS WITH AN ANALYTIC SOLUTION

Frederick W. Robbins

July 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Presently, two-dimensional, two-phase interior ballistic computer codes are being developed. One such code is TDNOVA. In this report, numerical simulations of TDNOVA are compared to an analytic solution of a one-dimensional problem in order to provide some checks on the accuracy and the cost of running the code. The problem considers the propellant completely burned at time-zero and was solved analytically by Love and Pidduck. The differences between the analytic solution and TDNOVA are on the order of

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0.1% for pressure, velocity, distances, and time. The calculations cost as little as $1.00 for a complete solution, requiring 2.27 cp seconds execution time on a CDC 7600 computer system.

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I. INTRODUCTION

Past attempts to simulate two-phase flow phenomena in cased ammunition have been very successful[1] using available one-dimensional, two-phase flow interior ballistic codes, such as NOVA.[2] However, high performance, bagged-charge artillery simulations have been only partially successful. This has led to the development of a two-phase flow, fully two-dimensional, axisymmetric, inviscid interior ballistic computer code, TDNOVA[3] which allows specific treatment of configural complexities associated with the charge/chamber interfaces. To test the initial version of the code for accuracy and efficiency of its numerical schemes, a solution to the problem solved analytically by Love and Pidduck[4] was obtained numerically with TDNOVA. This approach follows that of Schmitt and Mann.[5]

In the problem solved by Love and Pidduck, "It is supposed that a given mass of gas, which is initially in a uniform state, is contained in a segment of a tube of uniform section. At one end the segment of the tube is bounded by a fixed transverse section, and at the other end the tube is closed by a piston of given mass, which is initially at rest and is free to move along the tube without resistance. It is required to find the subsequent states of the gas and the motion of the piston."[4] Love and Pidduck referred to this as the Lagrange problem, therefore the term "Lagrange gun."

It should be pointed out that TDNOVA was designed to start with two phases present (a propellant and ambient gas). Since the Lagrange gun simulation has only one phase present at the initial time, minor modifications had to be made to the code. P. S. Gough, the developer of the code, made the necessary changes. The comparison of an analytic solution for the all-burnt case to the numerical solution of TDNOVA, of course, does not validate any of the physics associated with the two-phase flow but does provide information on the numerical schemes and code efficiency.

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[1] *F. W. Robbins, J. A. Kudzal, J. A. McWilliams, and P. S. Gough, "Experimental Determination of Stick Charge Flow Resistance," 17th JANNAF Combustion Meeting, CPIA Publication 329, Volume II, pp. 97-118, November 1980.*

[2] *P. S. Gough, "The NOVA Code: A User's Manual. Volume 1. Description and Use," IHCR 80-8, Naval Ordnance Station, Indian Head, MD, December 1980.*

[3] *P. S. Gough, "A Two-Dimensional Model of the Interior Ballistics of Bagged Artillery Charges," ARBRL-CR-00452, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1981 (AD A100751).*

[4] *A. E. A. Love and F. B. Pidduck, "Lagrange Ballistic Problem," Phil. Trans. Roy. Soc., Volume 222, pp. 167-226, 1921-22.*

[5] *J. A. Schmitt and T. L. Mann, "An Evaluation of the Alpha Code in its One-Phase Mode," ARBRL-MR-03081, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1981 (AD A098037).*

II. CODE STRUCTURE

TDNOVA in its normal mode considers the propellant package as a two-phase, two-dimensional region surrounded by one-phase (gas) regions of one-dimensional and lumped-parameter character, with a two-phase, one-dimensional central ignition system (centercore). As the propellant is ignited and burns and the radial pressure gradients decay below some user specified value, the code transforms the two-dimensional, two-phase representation of the propellant package to a one-dimensional, two-phase flow, with area change, representation. This resulting system of parallel, coupled, one-dimensional treatments of propellant charge, ullage, and centercore igniter is referred to as a quasi-two-dimensional representation. The availability of these two representations allows treatment of the Love and Pidduck problem in both the two-dimensional (2D) and quasi-two-dimensional (Q2D) modes. This procedure is appropriate because there are separate areas of coding used for each mode. Of course, the Q2D representation of this problem is just a one-dimensional solution since the ullage and centercore regions are represented as having zero thickness and the gas is assumed to be inviscid. The partial differential equations governing conservation of mass, momentum and energy, along with the necessary algebraic relations and boundary conditions, can be found in Reference 3.

III. DESCRIPTION OF THE PROBLEM

The problem parameters are illustrated in Figure 1 and entail a projectile mass of 50 kg, a charge mass of 12 kg, a projectile travel of 6 m, an initial chamber volume of 0.0300 m^3, a diameter of 150 mm, an initial pressure of 621.09 MPa, a molecular weight of 23.80 g/g-mol, a covolume of 1000 mm^3/g, and a ratio of specific heats of 1.220.

This specific problem was solved analytically by Pidduck using Love's formulation and the solution is tabulated for selected times up to projectile exit. The times were chosen such that the rarefaction wave was at a midpoint of the chamber or at either boundary (Table 1). Plots of these data are given in Figure 2.

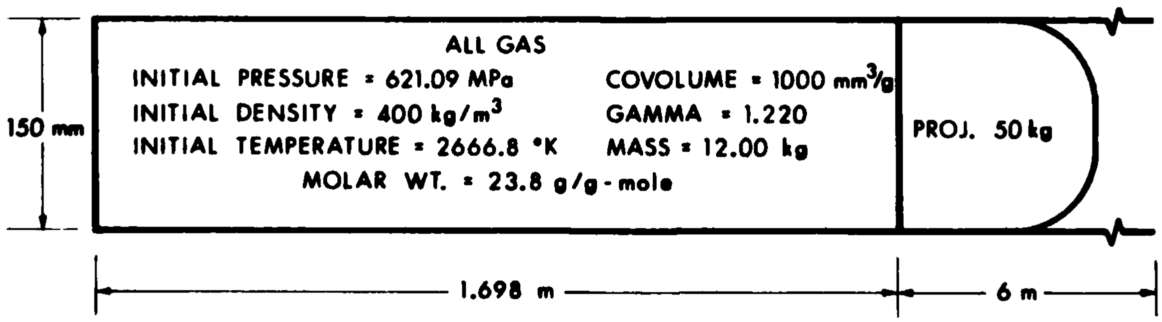

Figure 1. Lagrange Gun - Initial Conditions

TDNOVA was run with three mesh configurations, 16x3, 16x7, and 63x3 (axial by radial mesh points), for both modes of calculation, i.e., fully two-dimensional (2D) and quasi-two-dimensional (Q2D), which is, in this case, equivalent to a one-dimensional solution (Figure 3). It should be noted that for the Q2D configuration, the 63x3, 16x3, and 16x7 meshes are converted

TABLE 1. LOVE & PIDDUCK: ANALYTIC SOLUTION TO LAGRANGE GUN*

	t=0.0004772 P=6155 V=99.64 α= 0.18		t=0.0009544 P=5693 V=187.7 α= 0.40		t=0.001479 P=5015 V=275.4 α= 0.42		t=0.002117 P=4146 V=371.8 α= 0.332		t=0.002898 P=3218 V=466.2 α= 0.303		t=0.003859 P=2388 V=550.4 α= 0.332		t=0.00515- P=1664 V=632.5 α= 0.356		t=0.007137 P=1066 V=718.3 α= 0.331		t=0.01023 P=629.2 V=801.3 α= 0.312	
y_0	y	p	y	p	y	p	y	p	y	p	y	p	y	p	y	p	y	p
0(breech)	0	6333	0	6333	0	5171	0	4169	0	3316	0	2610	0	1728	0	1086	0	650.0
16.98	16.98	6333	17.06	6208	18.81	5170	21.20	4168	24.30	3316	28.08	2568	36.11	1727	49.93	1085	71.84	649.7
33.95	33.95	6333	34.41	6074	37.62	5168	42.38	4166	48.26	3314	56.38	2532	72.24	1725	99.89	1083	143.8	648.6
50.93	50.93	6333	51.69	5958	56.45	5164	65.60	4163	72.39	3312	84.84	2491	108.4	1721	150.1	1080	216.0	646.8
67.91	67.91	6333	69.28	5836	75.28	5159	84.78	4158	96.52	3309	113.6	2448	144.5	1715	200.2	1076	288.7	644.3
84.88	84.88	6333	87.06	5712	94.12	5152	106.0	4152	120.6	3304	142.8	2404	180.6	1708	250.5	1071	361.8	641.0
101.9	101.9	6196	105.0	5589	113.1	5040	127.2	4145	144.4	3241	172.4	2358	218.1	1676	301.0	1065	436.0	632.1
118.8	119.2	6059	123.3	5465	132.3	4929	148.4	4136	169.0	3174	202.3	2310	255.9	1643	351.7	1058	511.2	620.1
135.8	136.0	5923	141.6	5342	151.7	4818	169.6	4126	193.0	3109	232.6	2262	293.7	1609	402.6	1050	587.0	607.4
152.8	154.3	5787	160.2	5220	171.3	4707	190.7	4115	218.4	3041	263.2	2212	332.0	1574	453.9	1041	663.9	594.9
169.8	172.2	5651	179.0	5097	191.2	4599	212.0	4102	245.2	2970	294.1	2162	371.9	1535	505.4	1030	714.7	581.6

t = time from beginning of motion in seconds.
P = pressure in kg./cm^2 of cordite gas filling the space behind the projectile with uniform density.
V = velocity of projectile in m./sec.
α = coefficient necessary to make ½ $(M+\alpha C)V^2$ equal to work of uniform adiabatic expansion.
y_0 = initial distance of a plane of particles from the breech in cm.
y = distance of same particles at time t.
p = pressure in kg./cm^2.

*Phil. Trans. Roy. Soc. Vol. 222, 1921-22, TABLE 1.

internally by the code to a 63x1 or 16x1 mesh at time zero. This can be seen in Table 2 where the 16x3 Q2D run and 16x7 Q2D run are seen to be identical except for the cost figures, which contain the conversion from a 16x7 mesh to a 16x1 mesh. In subsequent tables and figures the 16x3 and 16x7 Q2D runs are referred to as 16xN.

All the calculations were performed such that tableaus of all the variables were printed out at the exact times reported by Pidduck and at muzzle exit. The values given without parentheses on subsequent plots are calculated values from TDNOVA and those with parentheses are from the table by Love and Pidduck, the percent difference being the percent difference between the calculated and analytic pressure values.

IV. RESULTS

It is seen that the 16x3 Q2D run is in close agreement with the analytical solution. Only marginal further improvement is therefore obtained with the 63x3 2D run. The results indicate that both the Q2D and the 2D algorithms are reasonably accurate, at least for this simple problem. The relative cost figures for the 16x3 Q2D and the 63x3 2D runs illustrate the potential economy inherent in conversion from a fully 2D to Q2D representation, at a suitable point, in more complex ballistic simulations.

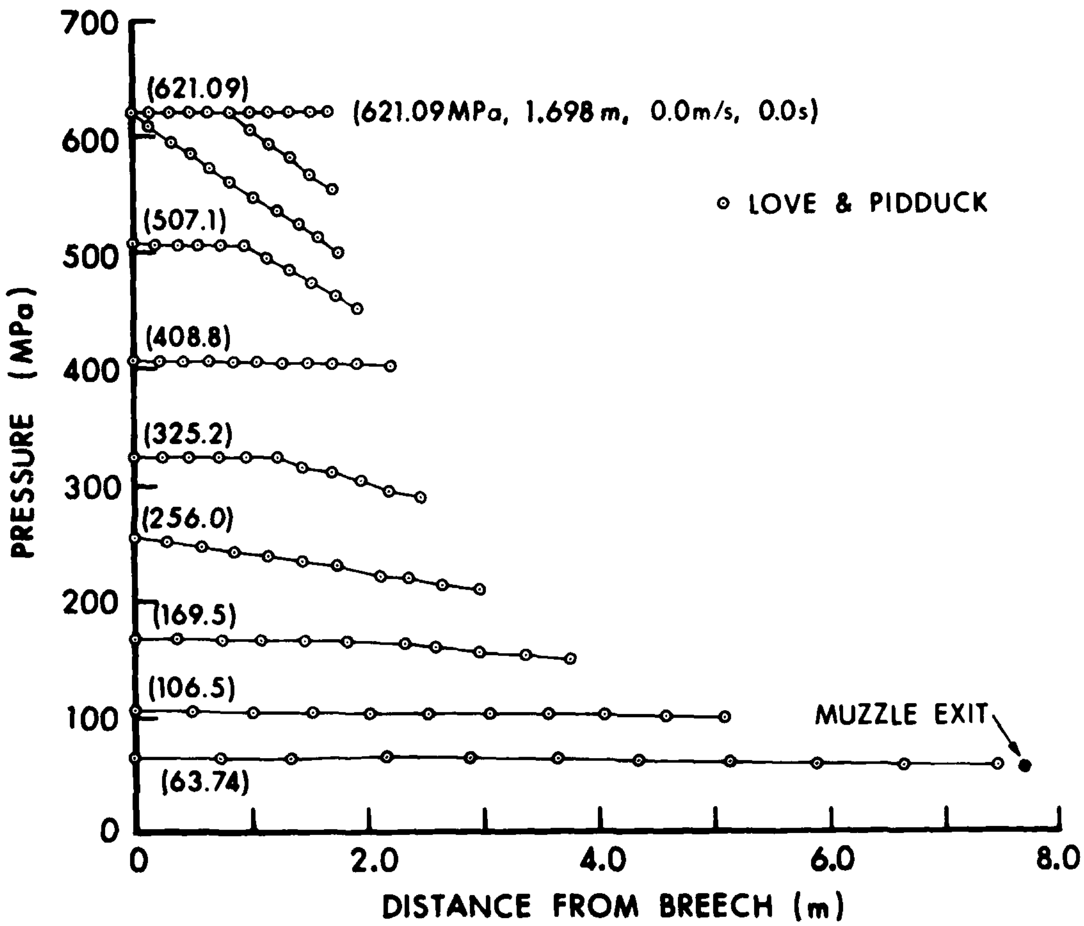

Figure 2. Lagrange Gun - Love and Pidduck Pressure Profiles

In Table 3 the % Diff columns need some explanation. The first of the three numbers in the % Diff box for one time is the percent difference between the 16xN Q2D and the 63x3 2D. The next number in the % Diff box is the percent difference between the 16xN Q2D and the analytic solution, and the last entry is the percent difference between the 63x3 2D and the analytic solution. Table 3 summarizes the difference between a 16xN Q2D, 63x3 2D and the analytic solution, all at the base of the projectile at the tabulated times of Love and Pidduck. These times occur when the rarefaction wave is at

TABLE 2. TDNOVA RESULTS WHEN PROJECTILE REACHES THE MUZZLE

Mesh	Mode	Exit Time (msec)	% Diff*	Gas Velocity m/s	% Diff*	Gas Pressure MPa	% Diff	# Steps	CPU Seconds	$ P6
16x3	Q2D	10.5833	0.030	807.86	0.027	54.401	0.390	103	1.996	$ .93
16x7	Q2D	10.5833	0.030	807.86	0.027	54.401	0.390	103	2.201	$ 1.03
63x3	Q2D	10.5782	0.017	808.49	0.098	54.407	0.400	405	22.010	$ 9.98
16x3	2D	10.5799	0.001	808.46	0.095	54.441	0.465	400	11.636	$ 5.28
16x7	2D	10.5813	0.012	808.29	0.073	54.487	0.548	1171	60.279	$27.24
63x3	2D	10.5779	0.020	808.53	0.103	54.408	0.402	515	59.558	$26.97
Analytic		10.58		807.7		54.19				

* From Love and Pidduck

TABLE 3. TDNOVA RESULTS AT PROJECTILE BASE

Mode	Time S	Pressure MPa	% Diff	Velocity m/s	% Diff	Distance from Breech cm	% Diff	Max. Diff
16 x N Q2D	.0004772	554.3	0.00	98.92	-.010	172.2	0.0	
63 x 3 2D		554.3	- .018	98.91	.723	172.2	0.0	
Analytic		554.2	- .018	99.64	.732	172.2	0.0	.732
16 x N Q2D	.0009544	500.0	0.00	187.7	0.0	179.1	0.0	
63 x 3 2D		500.0	- .020	187.7	0.0	179.1	- .059	-.059
Analytic		499.9	- .020	187.7	0.0	179.0	- .059	
16 x N Q2D	.001479	451.0	0.0	275.7	0.0	191.3	0.0	
63 x 3 2D		451.0	0.0	275.7	- .109	191.3	- .052	-.109
Analytic		451.0	0.0	275.4	- .109	191.2	- .052	
16 x N Q2D	.002117	395.7	-1.198	371.5	- .054	212.0	0.0	
63 x 3 2D		400.5	1.641	371.7	.081	212.0	0.0	1.641
Analytic		402.3	.447	371.8	.027	212.0	0.0	
16 x N Q2D	.002898	291.9	- .034	465.8	.086	244.9	0.0	
63 x 3 2D		291.8	- .206	466.2	.086	244.9	.122	-.206
Analytic		291.3	- .172	466.2	0.0	245.2	.122	
16 x N Q2D	.003859	212.5	- .047	550.2	.073	293.9	.034	
63 x 3 2D		212.4	- .236	550.6	.036	294.0	.068	-.236
Analytic		212.0	- .189	550.4	- .036	294.1	.034	
16 x N Q2D	.005154	151.2	- .062	632.1	.047	370.8	.027	
63 x 3 2D		151.1	- .465	632.4	.063	370.9	.296	-.456
Analytic		150.5	- .399	632.5	.016	371.9	.269	
16 x N Q2D	.007137	99.73	1.062	718.3	.083	505.3	.020	
63 x 3 2D		100.8	1.257	718.9	0.0	505.4	.020	1.257
Analytic		101.0	.198	718.3	- .084	505.4	0.0	
16 x N Q2D	.01023	57.34	- .087	800.9	.100	741.4	.054	
63 x 3 2D		57.29	- .526	801.7	.050	741.8	.040	-.526
Analytic		57.04	- .438	801.3	- .050	741.7	- .015	
16 x 3 Q2D	10.5833	54.40	.018	807.9	.074	769.8	---	
63 x 3 2D	10.5779	54.41	- .386	808.5	- .025	769.8	---	
Analytic	10.58	54.19	- .406	807.7	.025	769.8	---	-.406

the midpoint or at either boundary. The points when the rarefaction waves meet the boundary turn out to be numerically the points of greatest difference. The percent pressure differences at 2.117 ms and at 7.137 ms (when the rarefaction wave reaches the base of the projectile) for the 16xN Q2D mesh are further from the analytic solution than the 63x3 2D solution. The overall effect of these differences seems to be damped out over the entire ballistic cycle up to projectile exit in the sense that the ballistic parameters at muzzle exit are closer to the analytic solution. See Table 2 for examples of both 16x and 63x meshes.

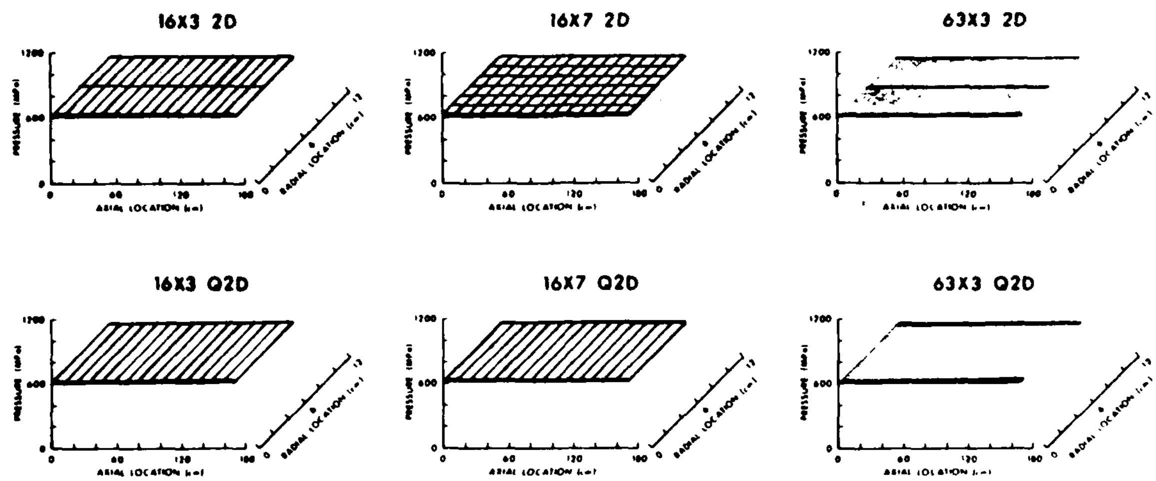

Figure 3. Initial Mesh Distribution - Lagrange Gun

Figures 4 and 5 are plots of pressure versus distance at specified times of the analytic solution against the 16x3 2D and 16xN Q2D TDNOVA runs, showing the excellent agreement for both the 2D and Q2D solution techniques with the same mesh size. Again note the small perturbation when the rarefaction wave reaches the breech (0 distance), which again gets damped out over the entire ballistic cycle.

Figure 6 is a plot of the spatially distributed analytic solution at different times, as in Figures 4 and 5, against the TDNOVA solution for a 63x3 2D run. The agreement is excellent.

In Figure 7, the first three times from Figure 6 are plotted on an expanded scale to look at the area where the derivative of pressure with respect to distance has a discontinuity because the rarefaction wave has not progressed all the way back into the undisturbed gas. The discontinuity is captured well with only about 0.2% difference at the discontinuity between the analytic and TDNOVA solution with the fine grid (63X3 2D). With the coarse grid (16XN Q2D), the error is larger, about 0.7%. In both simulations, a mesh point occurs at the slope discontinuity.

Figure 8 is a synopsis of the pressure at the base of the projectile, the velocity of the projectile, and the distance the projectile has traveled, all as functions of time, both for the analytic solution and a TDNOVA 16XN Q2D run. Again the agreement is excellent.

V. CONCLUSIONS

It is concluded that both the fully 2D and Q2D algorithms of TDNOVA yield results which are in close agreement with a specific analytic solution of the Lagrange problem. The differences between the analytic solution and TDNOVA are of the order of 0.1% for pressure, velocity, distance, and time except at times when the rarefaction wave intersects a solid boundary in which case the discrepancy is as much as 1.6% for a mesh of 16 axial points.

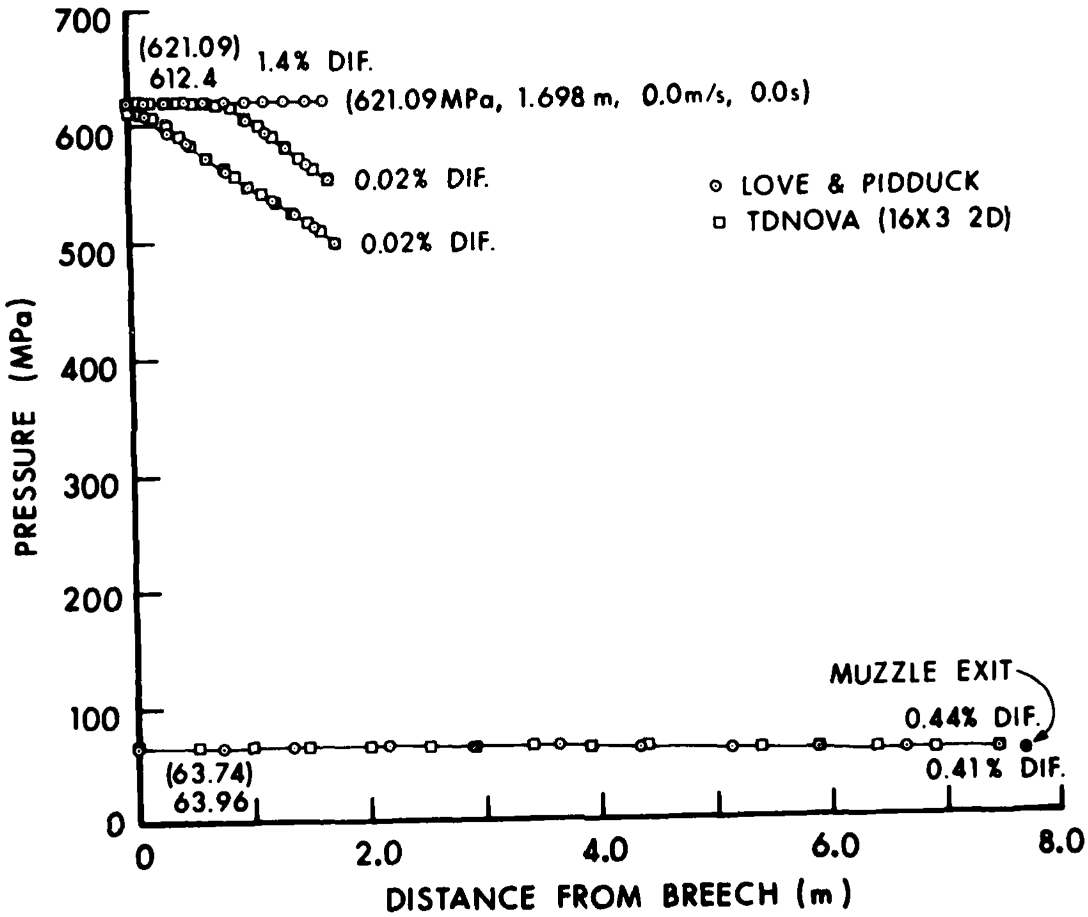

Figure 4. Lagrange Gun Comparison of TDNOVA 16x3 2D Run with Love and Pidduck Analytic Solution

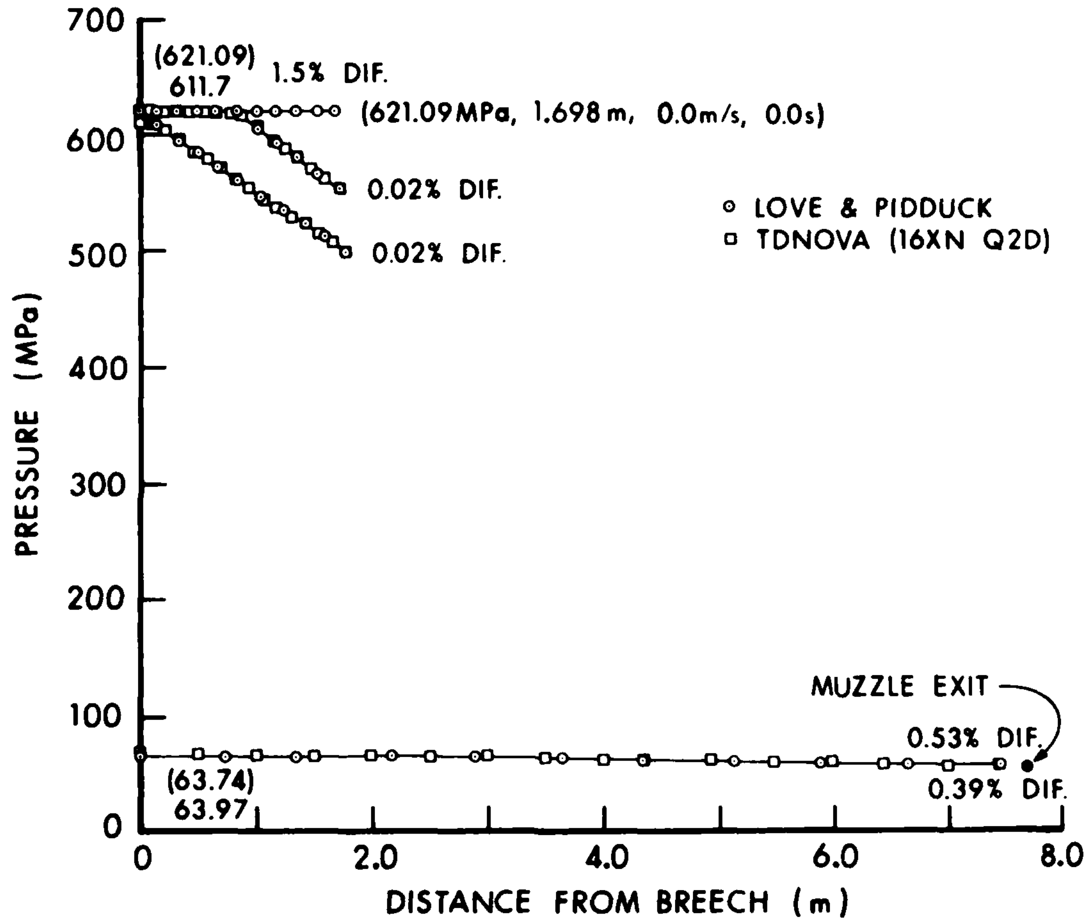

Figure 5. Lagrange Gun Comparison of TDNOVA 16xN Q2D Run with Love and Pidduck Analytic Solution

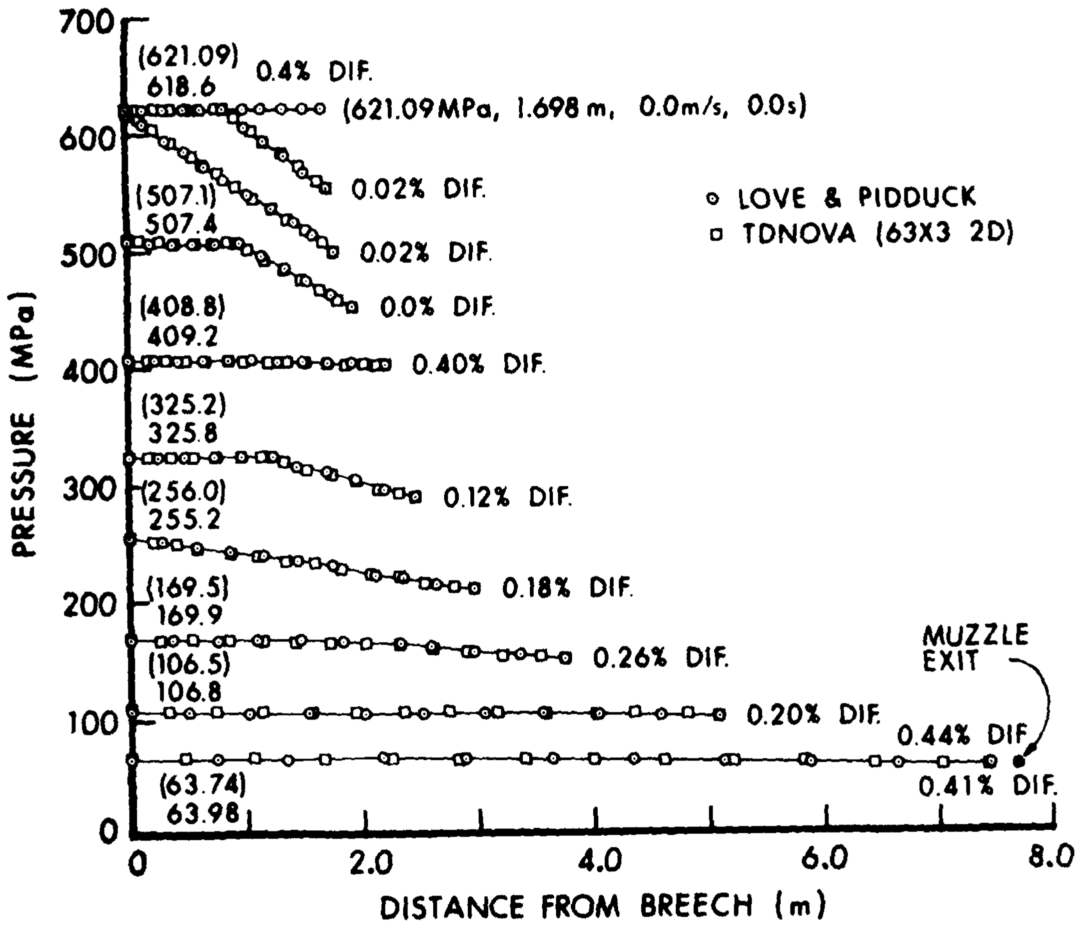

Figure 6. Lagrange Gun Comparison of TDNOVA 63x3 2D Run with Love and Pidduck Analytic Solution

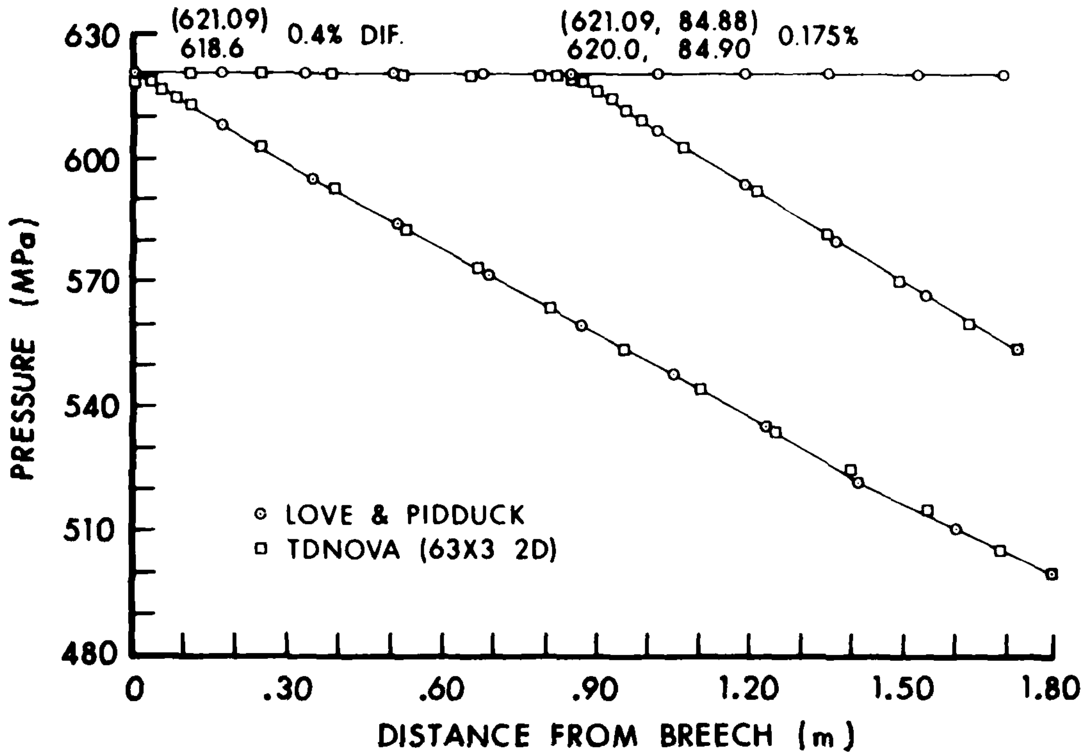

Figure 7. Expanded View of First Three Tableaus of TDNOVA 63x3 2D Run with Love and Pidduck Analytic Solution

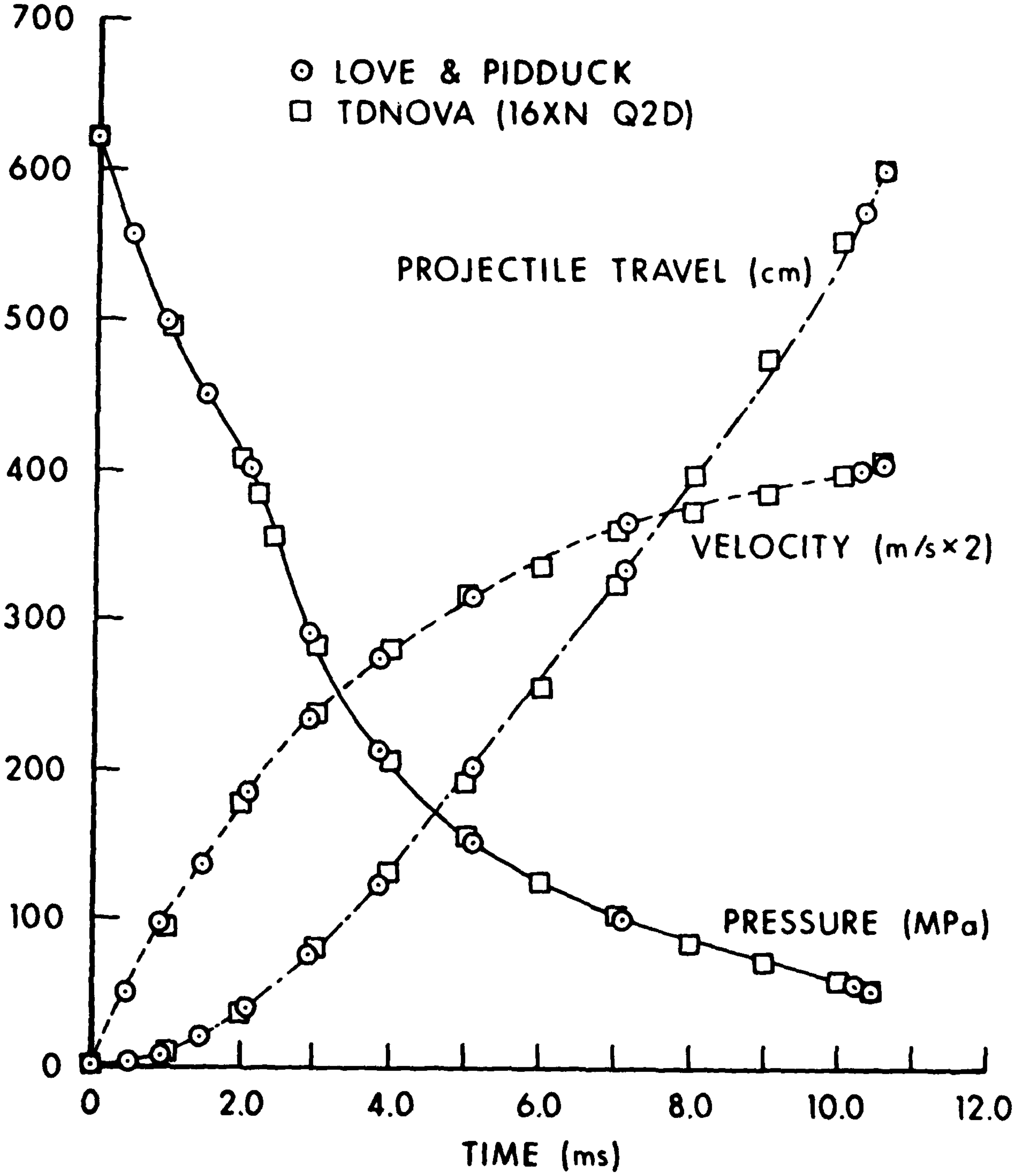

Figure 8. Pressure, Velocity, and Travel - Comparison of TDNOVA 16xN Q2D Run with Love and Pidduck Analytic Solution

ACKNOWLEDGMENTS

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